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Soft state of Cygnus X-1: stable disk and unstable corona

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ABSTRACT

Two component X–ray spectra (soft multicolor black body plus harder power law) are frequently observed from accreting black holes. These components are presumably associated with the different parts of the accretion flow (optically thick and optically thin respectively) in the vicinity of the compact source. Timing analysis further suggests that most of the aperiodic variability of the X–ray flux on the short time scales is associated with the harder component. In particular the RXTE spectra of Cygnus X–1 observed during soft state in June 1996 can be well represented as a sum of a constant soft component and strongly variable harder component. We suggest that drastically different amplitudes of variability of these two components are simply related to the very different viscous time scales in the geometrically thin (optically thick) and geometrically thick (optically thin) parts of the accretion flow.

In the geometrically thin disks variations of viscosity or mass accretion rate occurring at large radius from the black hole on the local dynamical or thermal time scales do not cause any significant variations of the mass accretion rate at smaller radii due to a very long diffusion time. Any variations on the time scales shorter than the diffusion time scale are effectively dampened. On the contrary such variations can easily survive in the geometrically thick (optically thin) flows and as a result the mass accretion rate in the innermost region of the flow will reflect modulations of the mass accretion rate added to the flow at any distance from the black hole. Therefore if principle instabilities operate on the short (dynamical or thermal) time scales then the stability of the soft component (originating from the geometrically thin and optically thick flow) and variability of the hard component (coming from the geometrically thick and optically thin flow) are naturally explained.

For Cygnus X-1 overall shape of the power density spectra (PDS) in the soft and hard spectral states can be qualitatively explained if the geometrically thin disk is sandwiched by the geometrically thick corona extending in a radial direction up to large distance from the compact object. In the hard state the thin disk is truncated at some distance from the black hole followed by the geometrically thick flow. The break in the PDS is then associated with the characteristic frequencies in the accretion flow at the thin disk truncation radius.

Key words: accretion, accretion disks – stars: individual (Cygnus X-1) – X–rays: general

1 INTRODUCTION

A well known characteristic of accreting stellar mass black holes is the presence of two drastically different spectral states, first discovered in Cygnus X-1 by Tananbaum et al. 1972 (see Tanaka and Shibazaki 1996 for review). In the **Soft** spectral state luminosity peaks at around 1 keV, while in the **Hard** state luminosity is dominated by photons with the energy of the order of 100 keV. This bimodality is believed to be related to very different regimes of the accretion flow in the vicinity of the black hole. Soft radiation is interpreted as a black body emission originating from the optically thick (geometrically thin) disk (Shakura, Sunyaev 1973), while hard emission, having a nearly power law shape at low energies and a cutoff above ~ 100 keV, should come from an optically thin and hot medium where comptonization of soft seed photons by the hot electrons plays an important role (e.g. Sunyaev and Truemper 1979). One of the popular models assumes that an optically thick disk is truncated at some distance from the black hole and followed by an optically thin and hot flow (see e.g. Thorne and Price 1975, Liang and Price 1977, Esin, McClintock and Narayan

1997, Meyer, Liu and Meyer-Hofmeister 2000). The hard and soft spectral states of the source may then correspond to the situation when an optically thick disk is truncated far from or close to the black hole respectively.

Another important property of the X–ray emission from black hole candidates is a strong aperiodic variability on time scales longer than 10 ms (see e.g. van der Klis 1994). The power density spectra are very different during different spectral states suggesting that the variability and spectral properties are closely linked.

Cygnus X–1 is the best studied accreting black hole in our Galaxy. Due to its brightness and persistent nature it was observed virtually by every X–ray observatory flown to date. The source was observed in different spectral states, also having very different properties of the short time scale variability. We discuss below qualitative model aimed to explain the changes in short time scale variability correlated with changes in the spectral shape.

2 VARIABILITY OF THE DISK AND CORONA

2.1 Constant and variable spectral components

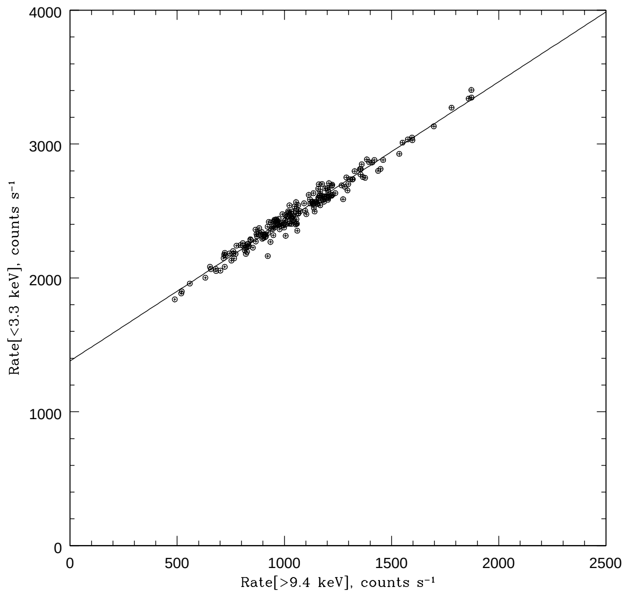
The state of the black hole candidates, when the spectrum contains a strong soft component, are usually called "High" or "Very High" states (e.g. Tanaka and Shibazaki 1996). This soft spectral component has a shape resembling multicolor black body emission and is believed to be produced by the standard optically thick (geometrically thin) disk of Shakura and Sunyaev (1973) type. Along with this "black body" emission a harder component is often present in the spectrum, with an approximately power law spectrum. Study of the variability properties of these two components led to the conclusion that most of the variability is associated with the power law component and not with the "black body" emission (see e.g. Miyamoto et al. 1994 for the GINGA observations of Nova Musca 1991). The same behavior have been observed for various sources manifested by the increase of the fractional RMS with energy. For the RXTE observations of Cygnus X–1 in the soft state in June 1996 Gilfanov, Churazov and Revnivtsev (2000) found that on the time scales shorter than 100 seconds the amplitude of the soft component variations is at least an order of magnitude lower than that of the harder component.

For illustration we plot in Fig.1a the PCA/RXTE (Brandt, Rotschild & Swank 1996) count rate in the soft (<3.3 keV) band as a function of the count rate in the hard band (>9.4 keV). The data points are the 16 s averaged values of the count rate from the "Standard Mode 2" format of PCA. The observation was performed in 1996 on June 4 and 16. From Fig.1a one can see that (i) relative amplitude of variations in the soft band ($S(t)$) is a factor of ~ 2 smaller than in the hard band ($H(t)$) and (ii) the correlation can be reasonably well approximated by a linear relation $S(t) = A + B * H(t)$, where $A > 0$. This relation is shown in Fig.1a with a straight line. One may interpret the fact that $A > 0$ as an evidence for the presence of a stable component in the soft band. Similarly good linear relation exists between the count rates in any pair of the PCA/RXTE channels. We then repeat the same procedure of fitting the linear relation between S and H for every energy channel setting S to the count rate in this channel $S(t) = S(t, E)$ and fixing $H(t)$ as a count rate above 9 keV. The resulting vectors $A(E)$ and $B(E)$ may be interpreted as the spectra of stable and variable components⋆. The spectra of constant and variable component are shown in Fig.1b. The stable component ($A(E)$) has a very soft spectrum (open circles in Fig.1b). For comparison the light grey line shows the spectrum of the multicolor black body disk emission with the characteristic temperature $T \sim 0.5$ keV. The "variable" component ($B(E)$) has a much harder spectrum (filled circles in Fig.1b) and does not contain a strong soft component (see Gilfanov et al. 2000 for details). Finally the two upper spectra (solid squares) were averaged over the periods of time when the count rate above 9 keV was high and low respectively. The thick grey lines show that these spectra can be reasonably well (within 10–15%) approximated by a combination $A(E) + I * B(E)$ where only I is allowed to vary. Note that these spectra contain data points separated by more than 11 days and intensity of the source vary (in the hard band) by at least a factor of $\sim$4 (see Fig.1a). Thus from this analysis one can conclude that spectra observed by RXTE in June 1996 can be reasonably well approximated by a combination of a constant soft component and a harder component which vary strongly in amplitude, but not much in shape. A very similar shape of the "variable" component can be obtained using the "Principle Component Analysis" or simply calculating the difference between the spectra averaged over the period of "high" and "low" count rates during the June 1996 observations.

2.2 Power density spectrum in the soft state

The typical power density spectrum (PDS) of the X–ray flux from Cygnus X-1 (in the 6–13 keV energy range) is shown in Fig.2a. In softer energy bands the PDS is very similar in shape, but has lower normalization, simply reflecting the larger contribution of the soft (stable) component to the source flux. The soft component was prominent in the Cygnus X-1 spectrum during these observations (even in the RXTE band, where the steep decline in efficiency precludes a useful spectral analysis below $\sim$3 keV). The characteristic temperature of the black body component is $\sim$0.5 keV and most of the source luminosity is clearly associated with it. Making the usual assumption that the black body component is due to an optically thick disk we inevitably come to the conclusion that the inner edge of the disk is rather close to the black hole. Perhaps it is as close as $6GM/c^2$ (i.e. the last marginally stable orbit for a Schwarzschild black hole), but a firm conclusion would require detailed spectral analysis, which is complicated because of the poor RXTE spectral response below 3 keV (see Gierliński et al. 1999 for the spectral analysis of Cygnus X-1 in the soft state). We make a conservative conclusion that the inner edge of the accretion

⋆ Note that although a good linear relation between S and H means that such deconvolution in two components is accurate enough, these two components may not necessarily have direct physical meaning.



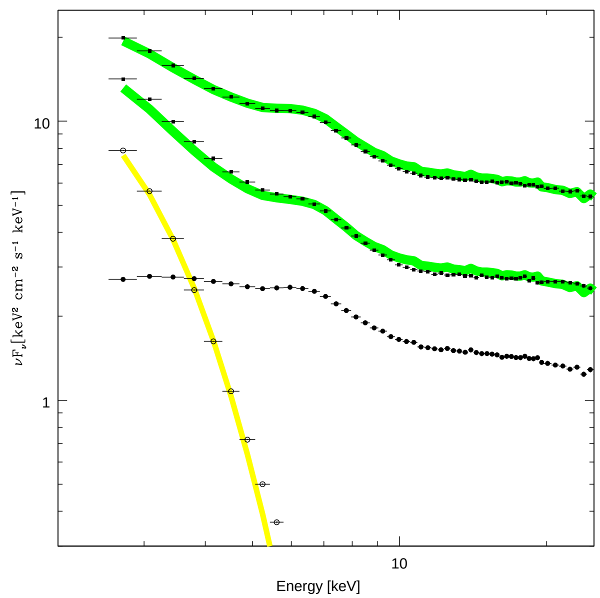


Figure 1. (Left:) The dependence of the count rate in the soft band (<3.3 keV) on the count rate in the hard band (>9.4 keV). Each data point represent 16 s averaged count rate (RXTE observations on 1996 June 4 and 16). **(Right:)** Spectra of "constant" (open circles – A(E)) and "variable" (solid circles – B(E)) components, derived from the linear fits of the correlation between count rate in different channels. For comparison the light grey curve shows the spectrum of a multicolor black body emission with a characteristic temperature of 0.5 keV. The two upper spectra (solid squares) were averaged over the periods of time when the count rate above 9 keV was high and low respectively. The dark grey lines show that these spectra can be reasonably well (within 10–15%) approximated by a combination of a constant and variable components $A(E) + I * B(E)$ where only I is allowed to vary.

disk (R_{in}) is at least well within $20GM/c^2$, where most of the gravitational energy of the accreting matter is released.

On the other hand the PDS of X–ray flux variations in this state (Fig.2a) holds the same shape (f^{-1}) from few 10^{-4} Hz up to 10 Hz. Because these variations are associated with the power law spectral component they presumably originate from an optically thin region. It is very unlikely that this extremely broad dynamic range of time scales (at least 4 orders of magnitude) can be provided by instabilities developing in the innermost region following R_{in}. This broad range of time scales (extending down to few 10^{-4} Hz) strongly suggests that the variations are due to instabilities occurring at much larger distances from the black hole and then propagating into the innermost region, where the energy is released (and X–ray photons are produced). The same slope of the PDS (f^{-1} – flicker noise) over broad range of frequencies also suggest the self-similar character of fluctuations. Lyubarskii (1997) considered the fluctuations of mass accretion rate associated with the fluctuations of the standard viscosity parameter α in the accretion flow. If the amplitude of α fluctuations at any radius is constant then variations of the mass accretion rate through the boundary, placed at much smaller radius, will have an f^{-1} power density spectrum.

Thus on one hand a stable optically thick disk extends down to a very small radii R_{in} (as indicated by strong and very stable soft component) and on the other hand prominent variations of the harder component are present in a broad range of time scales (up to at least 10^3–10^4 s – see Fig.2a), which are likely to be associated with instabilities occurring at much larger radii than R_{in}. The simplest explanation required to combine these two facts together is the assumption that along with a stable optically thick accretion disk a variable (optically thin) corona is present†. Various models involving optically thin corona have been discussed in the literature (e.g. Bisnovatyi–Kogan and Blinnikov 1976, Liang and Price 1977, Galeev, Rosner and Vaiana 1979, Haardt and Maraschi 1991, Esin, McClintock and Narayan 1997, Esin et al. 1998, Gierliński et al. 1999, see Poutanen 1998 for recent review). The configuration of the accretion flow we adopted is schematically shown in Fig.2b. Here the thick grey slab shows a stable (optically thick) accretion disk sandwiched by an optically thin corona. The "sine wave" with varying period schematically shows that the time scales of variations in the coronal flow increase with the radius. These variations (in mass accretion rate) are propagated down to the inner region of the main en-

† Of course it is impossible to exclude other possibilities. E.g. that seed fluctuations are embedded into the disk and are propagated down to the comptonization region where they affect the formation of the hard component. The only observational requirement on these fluctuations is that they should not affect emission of the optically thick disk. E.g. if we assume that ∼30% (rms) variations of the hard flux reflect similar variations of the mass accretion rate then we definitely can exclude the possibility that such variations (of the mass accretion rate) are coming through the optically thick disk

ergy release (shown by the thin box near the black hole) where observed X–ray emission is produced. In this picture one would then expect to observe the spectrum consisting of two components (soft stable component due to the disk emission and harder variable component due to comptonization in the corona). The relative contribution of these two components to the luminosity of an averaged spectrum would then reflect the ratio of the energy releases in the disk and corona (or mass accretion rates if no strong advection takes place in the corona). The PDS of the harder component may then have the same shape over broad range of frequencies (as observed – Fig.2a).

2.3 Power density spectrum in the hard state

Let us now consider what kind of PDS we can expect in the hard state. In the hard state the soft (black body) component is weak or absent suggesting that either the optically thick disk is truncated at a much larger radius (so that emission from the disk falls below X–ray regime) or that only a small fraction of the mass accretion rate is going through the optically thick disk, which in this case may extend all the way down to the last marginally stable orbit. We adopted below the former assumption and schematically show the configuration of the accretion flow in Fig.2b. Here the optically thick (stable) disk ends at some radius and it is followed by an optically thin flow which joins the coronal flow. We further assume that properties of this inner optically thin flow are similar (in terms of amplitude and characteristic time scales) to those of the corona. The PDS is then expected to have several distinct regions over frequency (the thick solid line in Fig.3a).

At high frequencies ($f \sim f_3$ in Fig.3a) there is a turnover of the PDS which may be due to the same reason as the turnover in the soft state PDS (Fig.2a). The discussion of this turnover is beyond the scope of this paper and we only briefly speculate on it in Section 3. Detailed analysis of the high frequency part of the Cygnus X–1 PDS is given in Revnivtsev et al., 2000.

The range of frequencies from f_2 through f_3 is associated with the variability scales corresponding to the optically thin region of the flow below the disk truncation radius. In this region we might expect the flow to be similar to the corona flow in the soft state and as a result the PDS should roughly reproduce the PDS in the soft state (i.e. $Power \propto f^{-1}$ for $f_2 < f < f_3$). Here f_2 is a characteristic frequency of the variability in the optically thin flow at the truncation radius of the disk. Below this frequency only a small fraction of accreting matter contributes to variability – the fraction of matter which goes through the corona. As a result a plateau on the PDS is formed for $f < f_2$. At even lower frequencies ($f < f_1$) oscillations due to the coronal flow start to be visible and the PDS again follows the f^{-1} law. The characteristic frequency, where plateau changes back to the f^{-1} law, is determined by the relation between the mass accretion rates in the corona and the disk. In other words the normalizations of two $f \propto f^{-1}$ regions on the PDS (one for $f < f_2$ and another for $f_2 < f < f_3$) differ by a factor of $A \sim \left(\frac{\dot{M}_{corona}}{\dot{M}_{disk}}\right)^2$. Thus the assumption of the variable corona on top of the stable disk (as inspired by the soft state data – Fig.2a) leads to a prediction of a specific shape of the PDS in the hard state. For comparison observed PDS in the hard state (for two RXTE observation in March 1996) are shown in Fig.3b. Variations in the PDS shape (in particular the shift of the break frequency) is then interpreted as the change of the disk truncation radius and the related change of the characteristic frequency. The expected change of the PDS caused by inward shift of the disk radius is shown by the dashed line in Fig.3a. Similar behavior of the PDS (correlated change of the break frequency and normalization of the band limited noise) was first reported for Cyg X-1 by Belloni & Hasinger (1990). When the disk truncation radius extends well down to the innermost region the PDS switches from the "3-breaks" shape to the "1-break" shape as observed in the soft state.

3 DISCUSSION

Discribed above is a qualitative picture inspired by the variability of the source during soft state. The suggested model is a phenomenological one and we speculate below on the possible underlying physics.

The first important question is why the thin disk is stable, while the corona is variable. Lyubarskii (1997) considered the power density spectrum arising from fluctuations of viscosity at different radii which causes fluctuations of the mass accretion rate. Fluctuations at one radius are related to the fluctuations at smaller radii through the Green function of the diffusion equation (Lynden–Bell & Pringle 1974, Lyubarskii 1997). In his picture fluctuations of viscosity at a given radius on the viscous time scales $t_{visc} \sim \frac{1}{\Omega_K \alpha (H/R)^2}$ causes fluctuations of the mass accretion rate at all smaller radii. Here Ω_K is a Keplerian angular frequency at a given radius R, α is viscosity parameter of Shakura & Sunyaev 1973, H is the half thickness of the disk. However because of the diffusive nature of the disk accretion any fluctuations of the mass accretion rate on time scales much shorter than the diffusion time scale at a given radius will not be propagated towards much lower radii (see Appendix), but instead will vanish (in amplitude) very close to the radius at which they originated. E.g. if we assume that actual fluctuations at a given radius are occurring at a time scales t_f, comparable with the dynamical time scales $t_d \sim \frac{1}{\Omega_K}$ or thermal time scales $t_{th} \sim \frac{1}{\Omega_K \alpha}$, then in the standard thin disk, where $H/R \ll 1$ ($H/R \sim 10^{-2}$ is a typical value for the standard geometrically thin disk, dominated by a gas pressure) we will always have $t_f \ll t_{visc}$. Therefore such fluctuations will never be propagated down to much smaller radii. Even if we consider the fluctuations occurring in the inner zone of the geometrically thin disk, which is emitting in X–rays (i.e. multicolor black body component directly observed by X–ray telescopes) we can easily show that the amplitude of fluctuations on a time scale $\sim t_f$ will be significantly suppressed after propagating a distance ΔR in a radial direction such as: $\frac{\Delta R}{R} \sim \sqrt{\frac{t_f}{t_{visc}}}$. For larger $\frac{\Delta R}{R}$ the amplitude of the mass accretion rate fluctuations will vanish. E.g. for fluctuations on the thermal scales $\frac{\Delta R}{R} \sim \frac{H}{R} \sim 10^{-2}$. Therefore $N \sim \frac{R}{H} \sim 100$ different ("incoherent") region over radius will contribute to the observed flux, effectively suppressing the fluctuations by a factor of $\sim \frac{1}{\sqrt{N}} \sim 10^{-1}$ even if the amplitude of fluctuations at any radius is large. Thus for the

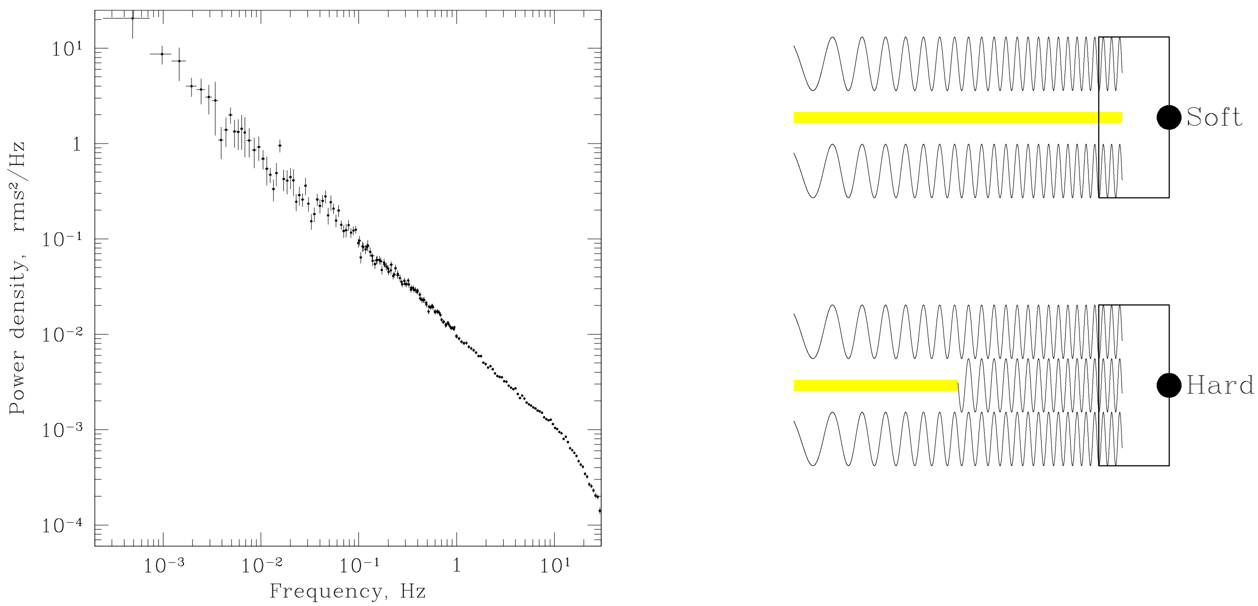


Figure 2. (Left:) Power density spectrum of Cygnus X-1 during June 1996 soft state (6-13 keV band, RXTE data). **(Right:)** Sketch of the adopted geometry for the soft and hard states of Cygnus X-1. The solid circle marks a position of a black hole. The box shown by thin lines shows the area where most of the gravitational energy is released and where most of the X–ray radiation is emitted. The grey 'slab' shows the optically thick (geometrically thin) accretion disk, which is truncated far from the energy release region in the hard state. Oscillating curves show schematically the different time scales of fluctuations in the mass accretion rate introduced into the optically thin (geometrically thick) flow at different radii. These fluctuations are then transported into the central region and cause the fluctuations of the observed X–ray flux.

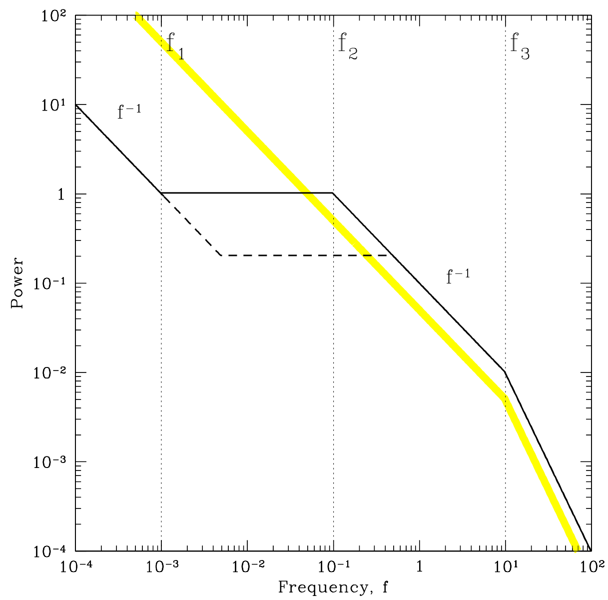
geometrically thin disk fluctuations of α (or mass accretion rate) on the dynamical of thermal time scales will not cause very prominent variations in the observed flux.

On the other hand geometrically thick disks (e.g. ADAF flows) are much more transparent for the high frequency oscillations. E.g. the fluctuation of the viscosity (α parameter) at some radius (at the dynamical or thermal time scales) will affect the mass accretion rate at all smaller radii and thus may provide fluctuations of observed flux coming from the innermost region of the accretion disk. Thus qualitatively the stability of the disk compared to the corona could be understood as the result of a much longer diffusion time in the disk, which suppresses propagation of fluctuations.

In the above model the characteristic frequencies are related to the position of the disk truncation radius: the smaller the truncation radius the higher the characteristic frequencies (in particular the break frequency). At least qualitatively this trend is consistent with correlation of the spectral and timing parameters observed in the black hole candidates. E.g. for Cygnus X–1 and GX 339–4 the increase of the characteristic frequencies correlates with the steepening of the spectra and the increase of the reflected component (Gilfanov et al., 1999, Revnivtsev et al., 2000), which may be related to the increase of the cooling of the Comptonization region by the soft photons from the disk and the increase of the fraction of the hard flux intercepted by the thin disk as it approaches black hole. In GRS1915+105 and XTE J1550–564 the QPO frequency, which in turn correlates with the break frequency, is well correlated with the soft component flux (e.g. Trudolyubov et al. 1999, Muno et al. 1999).

Of course the above representation of the PDS as a 3-break function is a gross oversimplification. In reality the shape of the PDS will be much more complex. E.g. broad humps may appear near the break frequency because the geometrically thin disk at the truncation radius supplies mass at a steady rate to the "unstable" inner geometrically thick region. In such conditions any increase of the accretion rate in the optically thin region must be followed by the decrease of the accretion rate at later moments of times (since total mass supply rate by the thin disk is constant). As a result a broad QPO–like hump may appear in the power density spectrum(Vikhlinin, Churazov, Gilfanov, 1994).

The truncation radius of the disk may fluctuate with time and affect the observed X–ray flux. Therefore even if the thin disk does not propagate the fluctuations of the mass accretion rate (at the frequencies higher than diffusion time) we may see fluctuations of the soft flux due to fluctuations of the disk truncation radius. The only case when we should expect the soft component to be very stable is when the disk extends all the way down to the marginally stable orbit at $\sim 3R_g$ (i.e. in the genuine soft state). In the "transition" state (i.e. when the disk is close enough to the black hole) fluctuations of the soft component due to disk truncation radius can be observed directly. In the hard state (when the disk is presumably truncate at a large distance from the compact source) emission of the thin disk is almost outside the X–ray band and variations of the soft disk flux can ob-



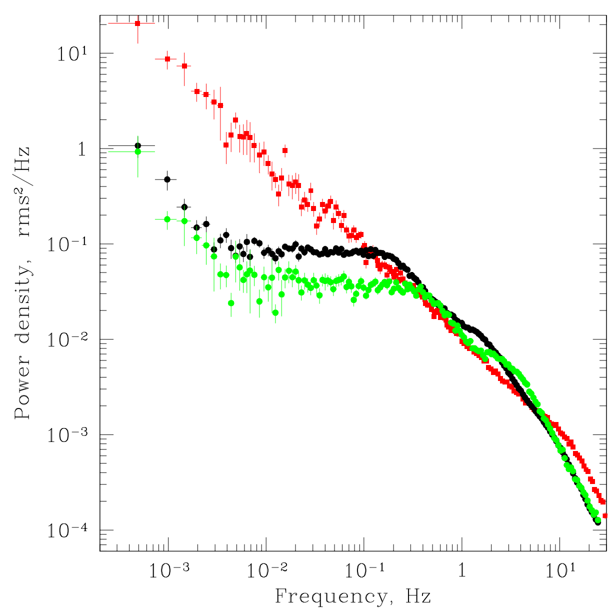


Figure 3. (Left:) The overall shape of the PDS expected in the simple geometry adopted here. In the hard state (thick solid line) there are three breaks (f_1,f_2,f_3 shown by thin vertical lines) in the power spectrum. f_2 is the characteristic frequency in the optically thin flow at the disk truncation radius. Anticipated changes in the power density spectrum associated with the inward motion of the disk truncation radius are shown by the dashed line. In the soft state the power spectrum (thick grey line) is a power law up to f_3. **(Right:)** Typical power density spectra of Cygnus X-1 in the hard (black and grey circles) and soft (black squares) states. The PDS are constructed from the RXTE data in the 6–13 keV energy range.

served indirectly through the influence of the soft flux on the comptonization region. E.g. variations of the soft flux entering the comptonization region with a given optical depth and energy release to the electrons will result in variations of both the flux and slope of the comptonized spectrum.

The high frequency turnover of the PDS (at about 10 Hz) may be related to the instabilities operating in the region of the main energy release. Part of the gravitational energy has already been released (and emitted) at larger radii. Therefore the amplitude of X–ray flux variations associated with the mass accretion rate fluctuations added to the flow in the inner region may be suppressed. Note that in the case of accretion onto a neutron star a large fraction of energy is released at the neutron star surface. Therefore this turnover may be absent in the power density spectra of the accreting neutron stars.

4 CONCLUSIONS

In the soft spectral state of Cygnus X-1, observed by RXTE in June 1996, the black body component was remarkably stable while the harder (power law like) component varied strongly on the frequency scales from 10 Hz down to 10^{-4}–10^{-3} Hz. We suggest that that such behavior is due to presence of an optically thin corona above the optically thick disk, which extends up to a large distance from the black hole. The variations of the mass accretion rate (or viscosity) occurring at a large distance from the compact object are propagated down to the region of the main energy release. The reason for different variability properties of the disk and corona (namely stable disk and unstable corona) may be due to the fact that in the optically thick (geometrically thin) disk any fluctuations at time scales shorter than the diffusion time scales $t_{visc} \sim \frac{1}{\Omega_K \alpha (H/R)^2}$ are effectively dampened and are not propagated down to small radii. The assumption that in the hard state the disk is truncated at some distance from the black hole (larger than the last marginally stable orbit) then naturally lead to an explanation of the overall shape of the power density spectra of black hole candidates in this spectral state.

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REFERENCES

Belloni T. and Hasinger G., 1990, A&A, 230, 103

Bisnovatyi-Kogan, G. S. and Blinnikov, S. I. 1976, Soviet Astronomy Letters, 2, 191

Brandt, H., Rotschild, R. & Swank, J. 1996, Memorie della Societa Astronomica Italiana, 67, 593

Esin A., McClintock J.E., Narayan R., 1997, ApJ, 489, 865

Esin, A. A., Narayan, R., Cui, W., Grove, J. E. and Zhang, S. 1998, ApJ, 505, 854

Galeev, A. A., Rosner, R. and Vaiana, G. S. 1979, ApJ, 229, 318

Gierliński, M., Zdziarski, A. A., Poutanen, J., Coppi, P. S., Ebisawa, K. and Johnson, W. N. 1999, MNRAS, 309, 496

Gilfanov M., Churazov E. and Revnivtsev M., 1999, A&A, 352, 182

Gilfanov M., Churazov E., Revnivtsev M., 2000, in preparation

Haardt, F. and Maraschi, L. 1991, ApJ, 380, L51

Liang E.P.T., Price R.H., 1977, ApJ, 218, 247

Lynden-Bell D. and Pringle J. E., 1974, MNRAS, 168, 603

Lyubarskii, Y. E., 1997, MNRAS, 292, 679

Meyer, F., Liu, B. F. and Meyer-Hofmeister, E. 2000, A&A, 354, L67

Miyamoto S., Kitamoto S., Iga S., Hayashida K. and Terada K. 1994, ApJ, 435, 398

Muno M. P., Morgan E. H. and Remillard R. A., 1999, ApJ, 527, 321

Poutanen, J. 1998, Theory of Black Hole Accretion Disks, eds. M.A. Abramowicz, G. Bjornsson, J.E. Pringle, Cambridge University Press, 100

Revnivtsev M., Gilfanov M. and Churazov E., 2000, A&A, submitted, astro-ph9910423

Revnivtsev M., Gilfanov M., Churazov E., Sunyaev R., 2000, A&A, to be submitted

Shakura N., Sunyaev R., 1973, A&A, 24, 337

Sunyaev R., Truemper J., 1979, Nature, 279, 506

Tanaka Y., Shibazaki N., 1996, A&A Rev., 34, 607

Thorne K.S., Price R.H., 1975, ApJ, 195, L101

Tananbaum, H., Gursky, H., Kellogg, E., Giacconi, R. and Jones, C. 1972, ApJ, 177, L5

Trudolyubov S., Churazov E. and Gilfanov M., 1999, Astronomy Letters, 25, 718

van der Klis M., 1994, ApJS, 92, 511

Vikhlinin A., Churazov E. and Gilfanov M., 1994, A&A, 287, 73

APPENDIX A1: DAMPENING THE VARIATIONS IN THE GEOMETRICALLY THIN DISK

In this appendix we formally demonstrate the natural fact that in a geometrically thin disk variations of the viscosity at some radius on a time scale shorter than the diffusion time scale causes negligible variations of the mass accretion rate at smaller radii.

Consider for simplicity a geometrically thin (gas pressure dominated) disk with the constant ratio $\frac{H}{R}$, where H is a half thickness of the disk and R is the distance from the compact object. Let us assume that viscosity (α parameter) suddenly increases in a narrow ring at some distance R_1 from the center. Following Lyubarskii (1997) the deviation of the mass accretion rate from the steady state value at the radius $R = r \cdot R_1$ is:

$$\dot{m}(r,t) \propto \frac{C^2}{t^2}\sqrt{r}e^{-\frac{C}{4t}(r^{3/2}+1)} \times \left[I_{-2/3}\left(\frac{Cr^{3/4}}{2t}\right) - rI_{1/3}\left(\frac{Cr^{3/4}}{2t}\right)\right] \quad \text{(A1)}$$

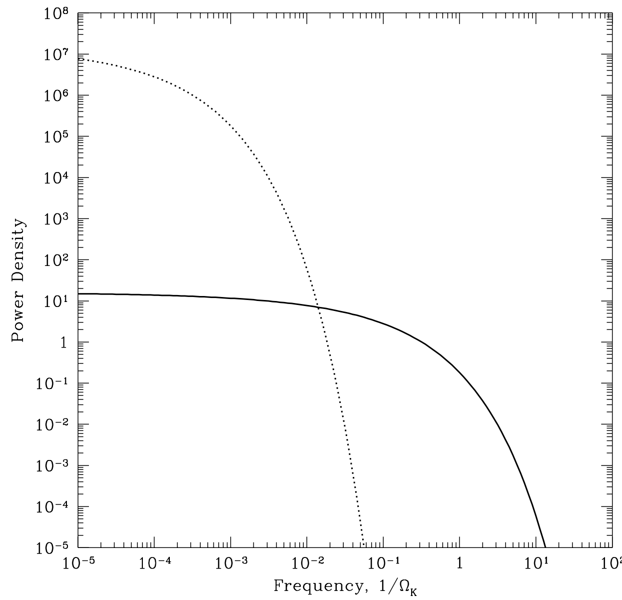

Figure A1. The power density spectrum of the mass accretion rate variations at some radius R caused by a sudden increase of viscosity (α parameter) in a narrow ring at the distance $R1 \gg R$. Here $\Omega_K = \sqrt{\frac{GM}{R_1^3}}$ is a Keplerian frequency at the radius R_1. The dotted line correspond to the case of a geometrically thin disk ($C \sim \frac{1}{\alpha(\frac{H}{R})^2} = 10^4$) and the solid line was obtained by formally setting C to unity.

where time t is expressed in units of $\frac{1}{\Omega_K}$ (here $\Omega_K = \sqrt{\frac{GM}{R_1^3}}$ is a Keplerian frequency at the radius $R1$), $C \sim \frac{1}{\alpha(\frac{H}{R})^2}$, $I_\nu(x)$ is the Bessel function of imaginary argument. The factor C is of the order of 10^4–10^6 for the standard geometrically thin (optically thick) gas pressure dominated disk and C decreases when the thickness of the disk increases. In the limit of $r \ll 1$ (i.e. at the radii much smaller than the radius R_1 where α is changing) the variations of the mass accretion rate is obviously:

$$\dot{m}(t) \propto \frac{C^{4/3}}{t^{4/3}}e^{-\frac{C}{4t}} \quad \text{(A2)}$$

The power density spectra associated with the variability in the form (A2) are shown in Fig.A1. Here the dotted curve corresponds to the case of $C = 10^4$ (i.e. the typical value in the standard geometrically thin disk). One can see that (as expected) virtually no variability is present at high frequencies comparable to Ω_K. For comparison the solid line shows the power density spectrum formally calculated for $C = 1$‡. Here significant variability is present up to high frequencies.

‡ Note that $C \sim 1$ necessarily means that disk is geometrically thick and the above equations, derived in the limit of a geometrically thin disk, are not applicable